ENVIRONMENTAL PROTECTION AGENCY

APTI 413: Cyclones

Student Manual Chapter 6

APTI: 413 CONTROL OF PARTICULATE MATTER EMISSIONS, 5TH EDITION

Student Manual

© C² Technologies, Inc.
11815 Fountain Way • Suite 200
Newport News, VA 23606
Phone 757.591.8900 • Fax 757.595.4169

The preparation of this manual was overseen by the organizations of the Environmental Protection Agency (EPA) and the National Association of Clean Air Agencies (NACAA*), and the revision of materials was coordinated and managed by the Tidewater Operations Center of C² Technologies, Inc., Newport News, Virginia.

Valuable research and feedback was provided by an advisory group of subject matter experts composed of Dr. Jerry W. Crowder, TX; Dr. Tim Keener, OH; Dr. Douglas P. Harrison, LA., and Mr. Tim Smith, Senior Air Quality Specialist, EPA, Office of Air Quality Planning and Standards.

Acknowledgements and thanks are also extended to Rutgers University, especially Francesco Maimone, Co-Director of the Rutgers Air Pollution Training Program, which hosted the pilot of the revised materials, and the additional reference sources that can be found throughout the manuals.

**The National Association of Clean Air Agencies (NACAA) represents air pollution control agencies in 53 states and territories and over 165 major metropolitan areas across the United States.*

State and local air pollution control officials formed NACAA (formerly STAPPA/ALAPCO) over 30 years ago to improve their effectiveness as managers of air quality programs. The associations serve to encourage the exchange of information among air pollution control officials, to enhance communication and cooperation among federal, state, and local regulatory agencies, and to promote good management of our air resources.

Table of Contents

Chapter

6

This chapter will take approximately 2.5 hours to complete.

OBJECTIVES

Terminal Learning Objective

At the end of this overview chapter, the student will be able to discuss the operation of cyclone collectors and use performance evaluation equations to estimate expected collection efficiency and pressure drop.

Enabling Learning Objectives

6.1 Summarize the operating principles of cyclone collectors.

6.2 Identify types of cyclone collectors.

6.3 Use performance evaluation equations to estimate expected collection efficiency of a cyclone collector.

6.4 Use performance evaluation equations to estimated expected pressure drop of a cyclone collector.

6.5 List instrumentation that would be helpful to inspectors evaluating cyclone performance.

Checks on Learning

Problem Examples

And

End of Chapter Review Questions & Problems

Cyclones

This chapter explores cyclones as particulate capture devices and demonstrates the different performance evaluations equations used to determine the efficiency of cyclone collectors.

Cyclone Collectors

Cyclone collectors use inertial force to separate particles from a rotating gas stream. There are two main types of cyclones: (1) large diameter cyclones and (2) small diameter multi-cyclones. Large diameter cyclones range in size from approximately 1 foot in diameter to more than 12 feet in diameter and are used for the collection of large diameter particulate matter that would otherwise settle out near the source and create a nuisance in the immediate area. Large diameter cyclones typically have operating pressure drops of 2 in WC to 4 in WC. Multi-cyclone collectors are groups of small diameter cyclones, typically 6 inches to 12 inches in diameter, which have better particulate removal capability than large diameter cyclones. The multi-cyclone units are used as stand-alone collectors on sources generating moderate-to-large particulate matter and are also used as pre-collectors to reduce the particle loading into fabric filters and electrostatic precipitators. Multi-cyclones typically have operating pressure drops greater than 4 in WC.

Cyclone collectors are occasionally used as pre-collectors in air pollution control systems vulnerable to ember entrainment. While the embers do not damage cyclone components, the hoppers must be properly designed to prevent the accumulation of combustible material that could be ignited. Simmering fires in the hoppers could warp the tube sheet supporting the multi-cyclone tubes, crack welds and gaskets used to seal the tubes to the tube sheet, and damage the hopper casings.

6.1 Operating Principles

Cyclones use inertial force to separate particles from a gas stream. Because the inertial force is applied in a spinning gas stream, the inertial force is often termed centrifugal force. The first step in particle capture is the accumulation of particles along the inner wall of the cyclone due to centrifugal force.

For vertically oriented cyclones, settling the particles into a hopper is the second step in the overall process of particle capture. However, unlike electrostatic precipitators and fabric filters, there is little if any particle agglomeration to facilitate gravity settling, until the particles reach the cyclone tube discharge. The particles settle at a rate that is dependent partially on their terminal settling velocities. These settling rates are quite small for particles less than 10 micrometers in diameter. Fortunately, most particles in vertical cyclones also retain some momentum toward the hopper due to the motion of the gas stream passing through the cyclone. The combined effect of gravity settling and the momentum from the gas stream are sufficient to transport the particles from the cyclone wall to the cyclone tube discharge, and eventually to the hopper.

The third step in the overall particulate matter control process is the removal of accumulated solids from the hoppers. This is an especially important step because the cyclone outlets extend directly into the hoppers. The presence of high solids levels due to hopper discharge problems could block the outlets and make the cyclone entirely ineffective for particulate removal.

Smaller diameter cyclones are more efficient than larger diameter cyclones.

Several factors affect the performance of a cyclone collector. The more important ones are the size and density of the particles, the gas velocity through the unit, the cyclone diameter, and the residence time of the gases in the cyclone (see Equation 4-28). Since inertial forces are used to separate the particles from the gas stream, collection efficiency increases as the size and density of the particle increases and as the gas velocity through the unit increases. Centrifugal force increases as the radius of turn decreases. As a result, smaller diameter cyclones are more efficient than larger diameter cyclones. Cyclones that have bodies and cones that are long relative to their diameter have longer residence times and higher collection efficiencies. As a result of these factors and others, a range of performance can be achieved with cyclones, as shown in Figure 6-1.

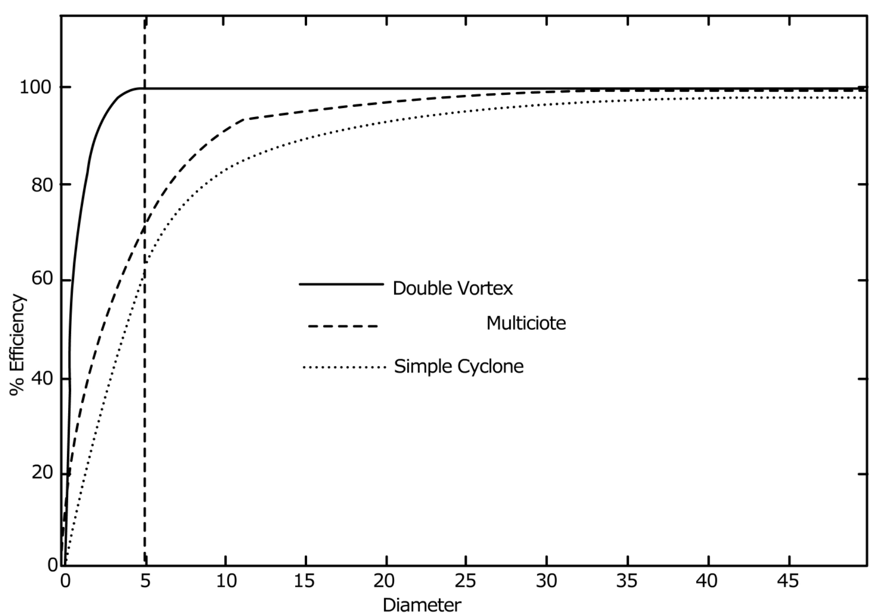


Figure 6-1. Cyclone fractional efficiency curves

In general, cyclones are not useful for the collection of sticky particulate matter. The main difficulties associated with these materials involve removal from the hoppers and build-up along the inner wall of the cyclone. Examples of hard-to-collect sticky material include partially polymerized oils, condensed high molecular weight organics, and ammonium sulfate and bisulfate particles. Sources emitting stringy material can cause build-up of material in the inlet vanes of multi-cyclone collectors. Partially blocked inlet spinner vanes do not generate the cyclonic flow patterns necessary for proper inertial separation.

Small diameter cyclones, including all multi-cyclone collectors, are vulnerable to severe erosion when treating gas streams having very large diameter particulate matter. Particles over twenty micrometers in diameter are very abrasive at the high tangential velocities achieved in the small diameter cyclones. The abrasiveness of particulate matter increases with the square of the particle diameter. Accordingly, cyclones handling particles in the twenty to more than one-hundred micrometer size range can be vulnerable to high erosion rates.

6.2 Large Diameter Cyclones

The inlet gas stream enters the large diameter cyclone through a tangentially mounted duct that imparts a spin to the gas stream. The inlet duct is usually at the top of the cyclone body, but large diameter cyclones may also have bottom inlets. Both arrangements are shown in Figure 6-2.

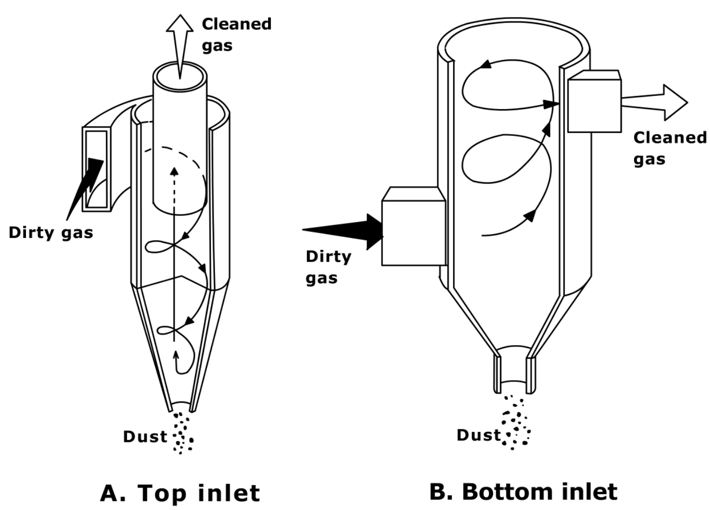


Figure 6-2. Large diameter cyclones

With the normal inlet gas stream velocity of 20 to 50 ft/sec, the gas stream spins approximately one-half to three complete rotations within the cyclone body of both types. An increase in the gas inlet velocity increases the spinning action of the gas stream, thereby improving inertial separation of the particles.

The gas flow pattern in a bottom inlet large diameter cyclone is relatively simple. The inlet gas stream begins to spin in the cyclone body because of the tangential inlet duct configuration. The gas stream forms an ascending vortex that rises up in the cyclone body to the outlet duct at the top of the unit. The particles that migrate across the gas streamlines settle by gravity when they approach the surface of the cyclone body where the gas velocity is low.

In the top inlet design, the gas stream spins in two separate vortices. The inlet stream creates an outer vortex due to the tangential location of the inlet duct and due to the presence of the outlet tube extension that prevents gas movement into the center of the cyclone body. As the gas stream passes down the cyclone body, it turns 180° and forms an inner vortex that moves toward the gas outlet tube at the top of the cyclone. The outlet tube must extend sufficiently far into the cyclone to facilitate formation of the outer vortex and to prevent a short-circuit path for the gas stream.

The particles that have migrated toward the outer portion of the outer vortex break away from the gas stream when it turns 180° to enter the inner vortex. Due to their inertia, the particles continue to move downward toward the cyclone hopper as the gas stream turns from the outer vortex to the inner vortex. The movement of the particles toward the hopper is controlled partially by inertial forces. The force of gravity also assists in particle movement toward the hopper.

Top-inlet, large-diameter cyclones can have a number of different inlet designs, as shown in Figure 6-3. The most common design is the simple tangential inlet (A). The deflector vane (B) reduces the gas stream turbulence at the inlet and can reduce the overall pressure drop. However, the deflector vanes can also impair vortex formation and thereby reduce particulate collection. Helical inlets (C) have been used in an attempt to reduce cyclone pressure drop and to improve performance. Involute entries (D) can also reduce turbulence-related pressure drop at the inlet. However, they usually provide improved efficiency due to the manner in which the outer vortex develops.

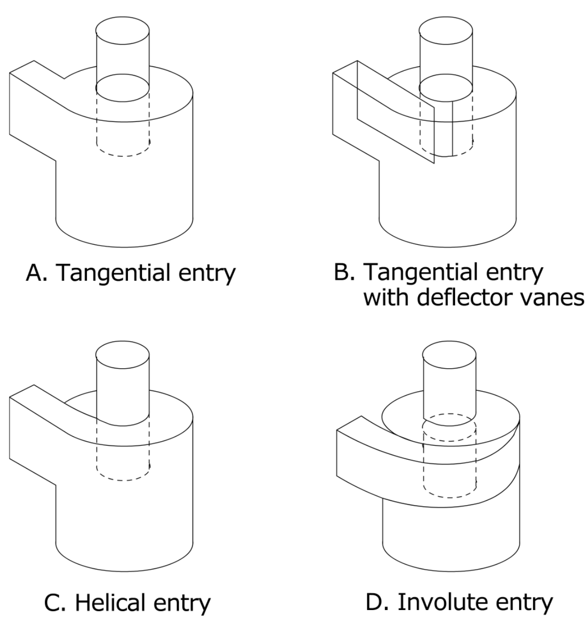
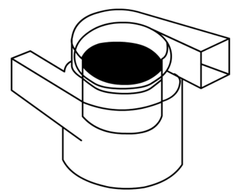
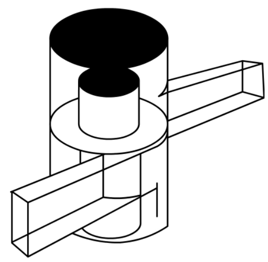


Figure 6-3. Types of cyclone inlets

The outlet gas tube is also an important consideration in the design of a large diameter cyclone. Some of the energy due to the radial motion of the ascending gases can be recovered by scroll devices (A) or outlet drums (B) placed on top of the outlet tube. These two cyclone enhancements, which are shown in Figure 6-4, are essentially flow straighteners that can effectively reduce the overall pressure drop across the unit without affecting the particulate matter removal efficiency.



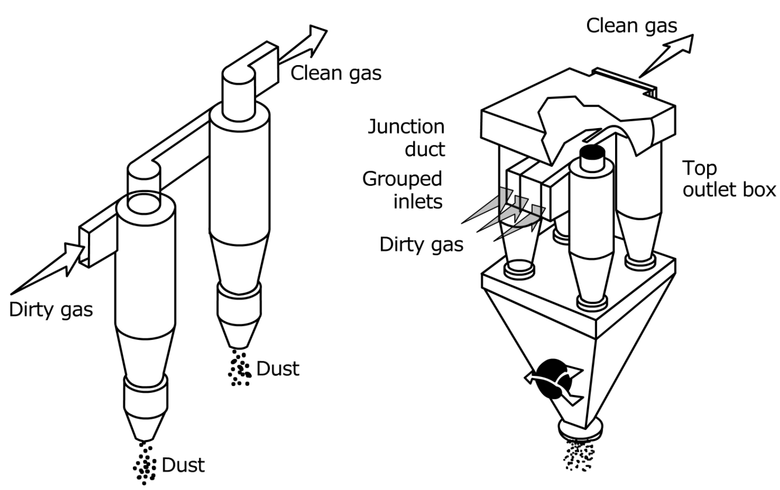
A. Involute scroll outlet



B. Outlet drum

Figure 6-4. Special outlet configuration for large diameter cyclones

Large diameter cyclones can be used in series or parallel arrangements in order to increase particulate matter removal efficiency or to increase gas flow capability. A series arrangement (A) of two cyclones of equal size and a parallel arrangement (B) of four cyclones of equal size are shown in Figure 6-5.



A. two cyclones in series
B. Four cyclones in parallel

Figure 6-5. Series and parallel arrangement of cyclones

The dust discharge system for a large diameter cyclone is similar to that used in other dry particle collectors and consists of a hopper for receiving the collected solids and a solids discharge valve that allows solids to be removed from the hopper without letting air in or out of the system. Four common types of solids discharge valves are shown in Figure 6-6. The slide gate (A), the rotary discharge valve (B), and the double flapper valve (D) are all capable of providing an airtight seal. The screw conveyer arrangement (C) cannot provide an airtight seal unless a solids discharge valve is placed between the bottom of the cyclone and the screw conveyor.

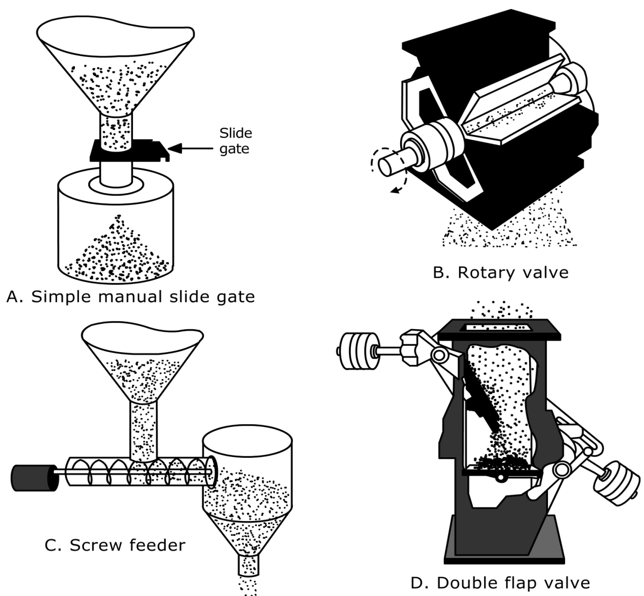


Figure 6-6. Types of solid discharge valves

Air infiltration into negative pressure cyclones, either through the solids discharge valve or through holes in the casing, can significantly reduce collection efficiency by disrupting the vortex and by entraining particles and carrying them toward the outlet flow. Also, collection of very large particles in high velocity vortices can be difficult because of the tendency for the particles to bounce off the wall.

6.3 Small Diameter Multi-Cyclones

The particulate matter removal capability of a small diameter cyclone is greater than that of a large diameter cyclone because the gas stream is forced to spin in smaller vortices, imparting greater inertial force to the particles. However, it is not possible to handle a large gas volume in a single small diameter tube. In order to treat the entire gas stream, a large number of small diameter tubes can be used in a single collector in which the tubes are in a parallel arrangement. Multi-cyclone collectors have cyclone tubes that range in size from 6 to 12 inches in diameter. A small multi-cyclone collector, such as the one shown in Figure 6-7, can have as few as 16 tubes. Large units may have several hundred tubes.

These units are divided into three separate areas by two tube sheets. The *dirty gas tube sheet* is mounted horizontally, supporting the cyclone tubes and separating the inlet gas stream from the hopper area of the unit. The *clean gas tube sheet* stair-steps down from front to back at approximately a 45° angle, dividing the inlet gas stream from the treated outlet gas stream. The outlet gas tubes from each of the cyclones pass through the clean gas tube sheet.

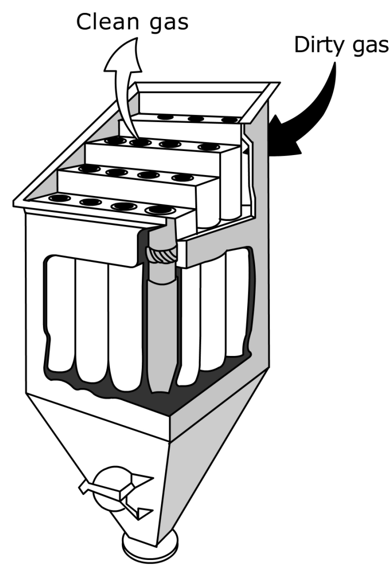


Figure 6-7. Multi-cyclone collector

Solids discharge valves are necessary under negative pressure multi-cyclone hoppers to prevent air infiltration upward through the hoppers and into each of the cyclone tubes. This air would impair cyclone particulate matter collection by disrupting the vortex of the inlet gas stream. Also, particles already in the hoppers could be entrained in the upward flowing air stream and driven out of the cyclone tube toward the outlet gas plenum.

A small diameter cyclone tube used in multi-cyclone collectors is shown in Figure 6-8. The gas stream entering the cyclone is spun as it passes over the turning vanes mounted at the inlet. The gas stream turns one-half to three times depending on the gas flow rate and the length and diameter of the cyclone. As in the case with large diameter cyclones, particles move toward the wall of the cyclone and subsequently fall by gravity. The gas stream turns 180° and passes out the center tube.

In large scale multi-cyclone collectors, the gas flow resistance of the outlet tubes can create an undesirable gas flow pattern called cross-hopper recirculation. As shown in Figure 6-9, the treated gas stream in the rows of cyclone tubes near the inlet can exit the bottom of the tube instead of the top, travel across the upper portions of the hopper, and pass upward through cyclone tubes near the back rows. This is possible due to the low gas flow resistance of the short outlet tubes for the cyclones on the back rows and the high gas flow resistance of the long outlet tubes for the inlet rows.

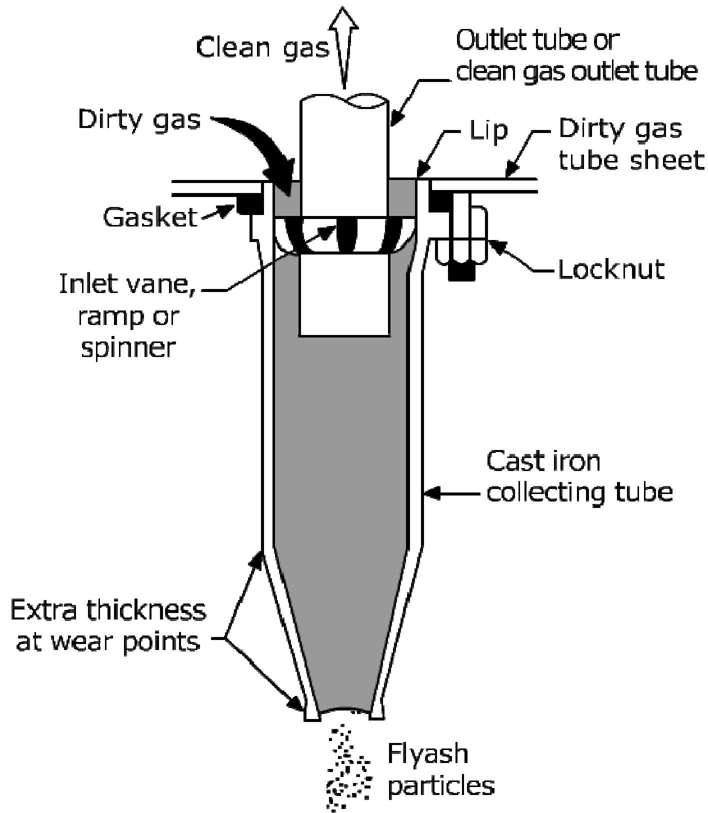


Figure 6-8. Cyclone tube used in multi-cyclone collector

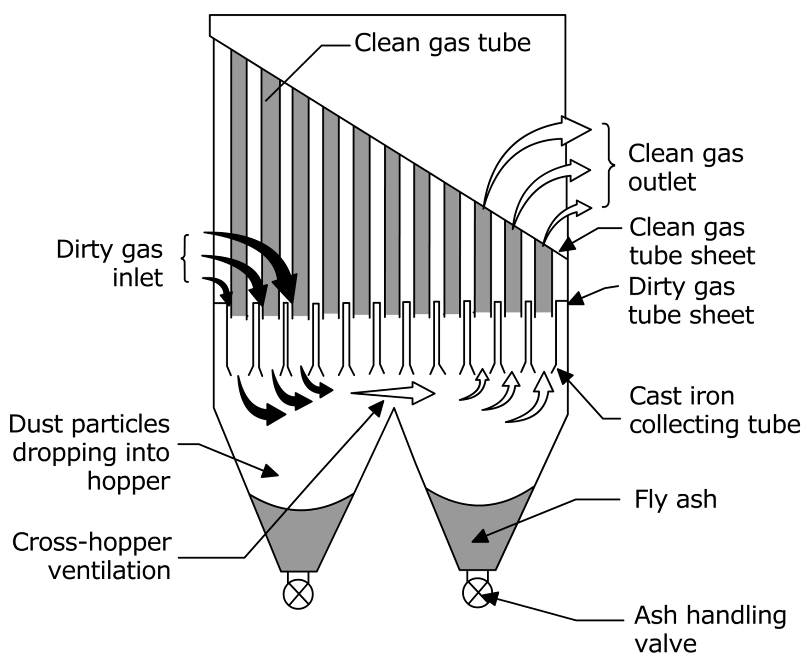


Figure 6-9. Cross hopper recirculation

Cross-hopper recirculation will increase particulate matter emissions, but can be avoided.

Particulate matter emissions are increased substantially by cross-hopper recirculation because the gas stream passing through the hopper re-entrains dust from the hopper and because this gas disrupts the vortex in the cyclone tube it reenters. Cross-hopper recirculation can be avoided by designing the outlet tubes to be of equal length throughout the collector or by placing baffles in the hopper to prevent gas flow from the front to the back of the unit.

The hoppers of cyclone collectors should be designed to minimize solids discharge problems. Solids accumulation in the hoppers can block the cyclone tube outlets of both large diameter cyclones and small multi-cyclone tubes. Several hopper design features are used to minimize hopper solids overflow.

- Solids discharge valve that properly seals
- Hopper throat of adequate size
- Hopper walls with adequate slope
- Strike plates or vibrators
- Thermal insulation

Cyclones generally use rotary discharge valves or double flapper valves (see earlier discussion) for the discharge of solids from the hoppers. These valves must be well maintained to minimize air infiltration up through the hopper and into the cyclone tubes. It is important to note that most cyclone collectors are located on the inlet (upstream) side of the fan and operate with negative static pressures in the range of –2 to –10 in WC in the hopper area. The solids discharge valve must be in good condition to maintain an air seal with these moderately high negative static pressures.

HINT

Rotary discharge valves and double flapper valves discharge solids from hoppers, but must be well maintained.

The hopper throat must be sized to allow for adequate solids flow. Solids bridging in the hoppers might occur when the throat is undersized. The necessary size of the throat depends on the sizes of particles collected, the tendency of particles to agglomerate in the hopper, and the temperature of the solids being withdrawn from the hopper. It is common practice to use throats of at least 10 inches diameter. In some large units, the throats are in the range of 12 to 24 inches.

The hopper walls must be sloped properly to allow for solids movement toward the hopper throat. Generally hopper valley angles are at least 60 degrees. This severe slope minimizes the tendency for material to cling to the walls. It is also helpful to minimize protrusions into the hopper from the wall. Obstacles, such as U-shaped hand holds, can provide an initial site for solids accumulation and bridging even when the hopper walls are properly sloped.

Strike plates are reinforced, anvil-like plates mounted on the exterior hopper walls in an area near the hopper throat. These plates protrude through any thermal insulation and outer lagging present around the hopper wall. The purpose of these plates is to provide a site where operators can apply a moderate force to dislodge solids accumulating on the side walls or bridging over the hopper throats. Without these strike plates, operators might be tempted to use a sledge hammer on the unreinforced hopper wall. Over time, the use of a sledge hammer on the unprotected hopper wall causes it to

Mounting strike plates on hopper walls and 2-4" of thermal insulation are two inexpensive ways to maintain a cyclone.

bulge inward. The hammer-related deflections can choke off the approach to the throat and provide sites for more severe solids accumulation. Mounting a strike plate provides an inexpensive means to minimize this hopper discharge problem.

On large cyclone systems, an electric vibrator can be used in lieu of a strike plate or in combination with the strike plate. The electric vibrator is used whenever the solids discharge valves are operating in order to gently force solids in the hopper to flow toward the hopper throat. Electrical vibrators are usually not economically reasonable for very small cyclone systems.

Thermal insulation is used around most mechanical collectors serving combustion sources. This helps to keep the solids hot and free flowing in the hoppers. It also minimizes stresses caused when the interior surface of metal is exposed to the 250°F to 600°F gas stream temperature while the exterior surface is exposed to ambient temperatures. It is common to install 2 to 4 inches of either mineral wool or fiberglass as insulating material around hoppers. In some cases, designers include an air gap and air stops under the thermal insulation to improve the insulating effect.

6.4 Performance Evaluation

Collection Efficiency

Two methods will be presented for evaluating the efficiency of a cyclone collector. The first is an older method, developed by Lapple (1951), for estimating the fractional efficiency of the average or standard cyclone. It is a relatively simple technique, but does not allow consideration of specific cyclone dimensions. Efficiencies determined with this technique should be considered only approximations. The second method was developed more recently by Leith, et al (1973). It is mathematically more complex, but allows consideration of the specific cyclone dimensions.

Lapple Technique

The first step in this procedure is the calculation of the particle size collected with 50% efficiency, termed the cut diameter, using the following equation:

(6-1)

$$[d_p]_{cut} = \sqrt{\frac{9\mu_g B_c}{2\pi n_t v_i \rho_p}}$$

Where

$[d_p]_{cut}$ = cut diameter (ft)
μ_g = gas viscosity (lb_m/ft . sec)
v_i = inlet gas velocity (ft/sec)
ρ_p = particle density ((lb_m/ft^3)
B_c = cyclone inlet width (ft)
n_t = number of turns

(6-2)

$$n_t = \frac{v_i t}{\pi D}$$

Where

t = residence time (sec)
D = cyclone diameter (ft)

(6-3)

$$t = \frac{V_{cyclone} - V_{outlet\ core}}{Q}$$

Where

$V_{cyclone}$ = total volume of cyclone (ft^3)
$V_{outlet\ core}$ = volume of outlet core [calculated from outlet pipe diameter] (ft^3)
Q = volumetric flow rate (ft^3/sec)

The cut diameter is a characteristic of the cyclonic control device and should not be confused with the geometric mean particle diameter of the particle size distribution. The cut diameter takes into account the gas stream inlet velocity, the cyclone inlet width, the gas viscosity, and other factors that influence particle removal in the cyclone. The second step is to calculate the $[d_p]_i/[d_p]_{cut}$ ratio for each particle size of interest. Finally, the fractional efficiencies, η_i, for each $[d_p]_i/[d_p]_{cut}$ ratio are read from Figure 6-10. These efficiencies may be used directly or they may be plotted against $[d_p]_i$ to form a fractional efficiency curve for a specific cyclone operation.

HINT

<u>Lapple Technique</u> offers a range of efficiency approximation <u>Leith Technique</u> offers more specific cyclone dimensions, but is a more complex procedure

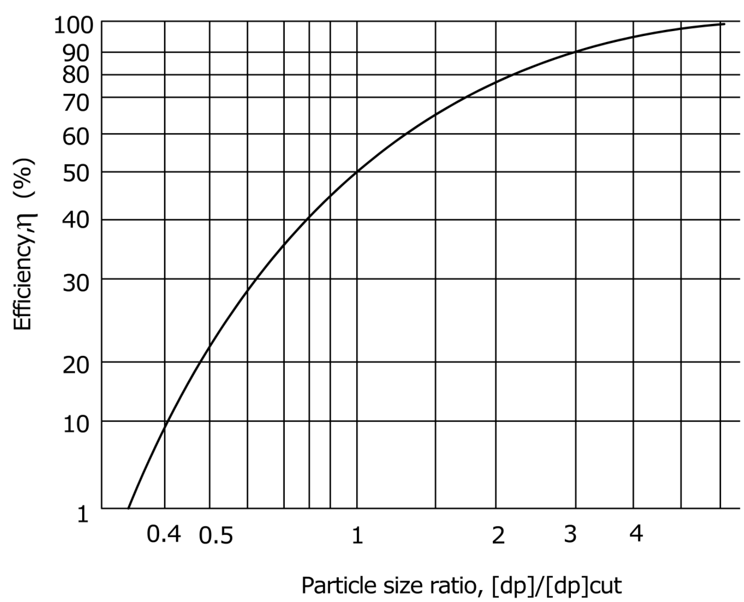


Figure 6-10. Lapple cyclone efficiency curve

These efficiency values give the estimated performance characteristics of a cyclone at the operating conditions used to estimate $[d_p]_{cut}$. Because this procedure only gives a very approximate estimate, a range of cut diameters is often used instead of a single value. Maximum and minimum efficiency curves determined from these values will then give a range of efficiencies for evaluation purposes.

Example 6-1 A large diameter cyclone is being used for the removal of grain dust in the range of 8 to 100 μm diameter. What are collection efficiencies over this range if the cyclone has an inlet width of 1 ft, an inlet gas velocity of 50 ft/sec, and an operating temperature of 68°F? Assume n_t = 1 and a particle density of 80 lb_m/ft^3.

Solution:

$$[d_p]_{cut} = \sqrt{\frac{9\mu_g B_c}{2\pi\pi(1}} = \sqrt{\frac{9\left(1.21x10^{-5}\ {lb_m}/{ft\cdot sec}\right)(1\,ft)}{2\pi\pi(1\left(50\ {ft}/{sec}\right)\left(80\ {lb_m}/{ft^3}\right)}} = 6.58x10^{-5}\,ft$$

$$=20\mu m$$

Estimate efficiency of 8, 12, 20, 30, 50 and 100 μm diameter particles:

Example 6-1 Efficiency Estimates		
$[d_p]_i$ (μm)	$[d_p]_i/[d_p]_{cut}$	η_i (%)
8	0.40	9
12	0.60	28
20	1.00	50
30	1.50	65
50	2.50	85
100	5.00	98

Leith Technique

The fractional efficiency equation of Leith and Licht is similar to many equations developed for particulate control devices:

(6-4)

$$\eta_i = 1 - e^{-2(C\Psi)^{\frac{1}{2n+2}}}$$

Where

η_i= efficiency for particle diameter i (dimensionless)
C= cyclone dimension factor (dimensionless)
Ψ= cyclone inertial impaction parameter
n = vortex exponent (dimensionless)

The following steps are involved in the solution of Equation 6-4:

1. Calculate n from Equation 6-5, using Equation 6-6 to adjust the value from ambient to elevated temperature, if necessary:

(6-5)

$$n = \frac{(12D)^{0.14}}{2.5}$$

Where

D = cyclone diameter (ft)

(6-6)

$$\frac{1-n_1}{1-n_2} = \left(\frac{T_1}{T_2}\right)$$

Where

n_1 = vortex index at ambient temperature (dimensionless)
n_2 = vortex index at elevated temperature (dimensionless)
T_1 = ambient absolute temperature (°R)
T_2 = elevated absolute temperature (°R)

2. Calculate the vortex natural length, ℓ, and compare this with the value of the dimension (H - S):

(6-7)

$$\ell - 2.3D_e\left(\frac{D^2}{ab}\right)^{1/3}$$

Where

ℓ = vortex natural length (ft)
D = cyclone diameter (ft)
a = cyclone inlet height (ft)
b = cyclone inlet width (ft)

Calculate H-S, where

H-S = overall cyclone height - outlet pipe length

A. If ℓ <(H-S), calculate $V_{n\ell}$:

(6-8)

$$Vn\ell = \frac{\pi D^2}{4}(h-S) + \frac{\pi D^2}{4}\left(\frac{\ell - S - h}{3}\right)\left(1.0 + \frac{d}{D} + \frac{d^2}{D^2}\right) - \frac{\pi D_e^2 \ell}{4}$$

(6-8a)

$$d = D - (D - B)\left(\frac{\ell - S - h}{H - h}\right)$$

Where

V_{nl} = volume of cyclone at natural length (ft^3)
D = cyclone diameter (ft)
h = height of upper cylindrical body of cyclone (ft)
S = outlet pipe length (ft)
ℓ = vortex natural length (ft)
D_e = outlet pipe diameter (ft)
H = overall cyclone height (ft)

B. If ℓ >(H-S), calculate V_H:

(6-9)

$$V_H = \frac{\pi D^2}{4}(h - S) + \frac{\pi D^2}{4}\left(\frac{H - h}{3}\right)\left(1.0 + \frac{B}{D} + \frac{B^2}{D^2}\right) - \frac{\pi D_e^2}{4}(H - S)$$

Where

V_H = volume of cyclone below end of exit pipe (ft^3)
B = dust outlet diameter (ft)

2. Calculate K_c using either V_{nl} or V_H:then calculate V_s

(6-10)

$$K_c = \frac{V_s + \frac{V_{nl}}{2}}{D^3} \text{ or } K_c = \frac{V_s + \frac{V_H}{2}}{D^3}$$

(6-10a)

$$V_s = \frac{\pi\left(S - \frac{a}{2}\right)\left(D^2 - D_e^2\right)}{4}$$

Where

K_c = cyclone volume constant (dimensionless)

V_S = annular shaped volume above exit duct to midlevel of entrance duct (ft^3)
V_{nl} = volume of cyclone at natural length (ft^3)
V_H = volume of cyclone below end of exit pipe (ft^3)
S = outlet pipe length (ft)
D = cyclone diameter (ft)
D_e = outlet pipe diameter (ft)
a = cyclone inlet height (ft)

4. Calculate the cyclone dimension factor:

(6-11)

$$C = \frac{8K_C}{K_a K_b}$$

Where

C = cyclone dimension factor (dimensionless)
K_a = cyclone inlet height divided by the cyclone diameter, a/D (dimensionless)
K_b = cyclone inlet width divided by the cyclone diameter, b/D (dimensionless)
K_c = cyclone volume constant (dimensionless)

1. Calculate the cyclone inertial impaction parameter for a single particle size:

(6-12)

$$\Psi = \frac{\rho_p d_p^2 u_{T_2} (n-1)}{18\mu_g D}$$

(6-12a)

$$u_{T_2} = \frac{Q}{ab}$$

Where

Ψ = cyclone inertial impaction parameter (dimensionless)
ρ_p = particle density (lb_m/ft^3)
d_p = particle diameter (ft)
u_{T2} = tangential velocity of particle at cyclone wall (ft/sec)
μ_g = gas viscosity ($lb_m/ft \cdot sec$)
D = cyclone diameter (ft)
n = vortex exponent (dimensionless)
Q = gas flow rate (ft^3/sec)
a = cyclone inlet height (ft)

b = cyclone inlet width (ft)

6. Using the values of C, Ψ and n, determine the collection efficiency using Equation 6-4.

7. Repeat the calculation of Ψ for a series of particle sizes and determine the efficiency for each size.

This technique is more complex than that of Lapple. However, it allows consideration of the actual cyclone dimensions and, when compared to experimental data, gives more accurate estimates. An excel spreadsheet is available from your instructor to ease some of the pain in using this method.

Pressure Drop

The pressure drop across a cyclone is an important parameter for the operator of the equipment. Increased pressure drop means greater costs for power to move exhaust gas through the control device. With cyclones, an increase in pressure drop usually means that there will be an improvement in collection efficiency.

HINT

Decrease in pressure drop = decreased efficiency and higher cost to operate.

One method for estimating pressure drop is based on the velocity head and the inlet and outlet dimensions of the cyclone:

(6-13)

$$\Delta P = 0.003 K_c P_g v_g^2 \left[\frac{ab}{D_e^2} \right]$$

Where

ΔP = static pressure drop (in WC)
K_C = 16, for tangential inlet; 7.5, for inlet vane (dimensionless)
o_g = gas density ($1b_m/ft^3$)
v_g = inlet velocity (ft/sec)
a = cyclone inlet height (ft)
b = cyclone inlet width (ft)
D_e = outlet pipe diameter (ft)

An alternate method bases the pressure drop on the velocity head, but includes all other effects in a single constant:

(6-14)

$$\Delta P = K_p P_g V_g^2$$

Where

ΔP = static pressure drop (in WC)
K_P = 0.013 to 0.024 (dimensionless)
ρ_g = gas density ($1b_m/ft^3$)
v_g = inlet velocity (ft/sec)

Example 6-2 A single high efficiency cyclone has an inlet width of 2 ft, an inlet height of 5 ft and an outlet pipe diameter of 5 ft. Estimate the pressure drop when the inlet velocity is 50 ft/sec and the gas temperature is 68°F.

Solution

Using Equation 6-13:

$$\Delta P = 0.003 K_c P_g V_g^2 \left[\frac{ab}{D_e^2}\right]$$

$$= 0.003(16)\left(0.075 \, {}^{lb_m}\!/_{ft^3}\right)\left(50 \, {}^{ft}\!/_{sec}\right)^2 = 3.6 \text{inWC}$$

Using Equation 6-14:

Since this is a high efficiency cyclone design, assume Kp = 0.024

$$\Delta P = K_p P_g V_g^2 = 0.024\left(0.075 \, {}^{lb_m}\!/_{ft^3}\right)\left(50 \, {}^{ft}\!/_{sec}\right)^2 = 4.5 \text{inWC}$$

Instrumentation

There are usually few instruments on cyclone collectors, due primarily to their small size and service requirements. On moderate-to-large systems, the following instruments might be useful.

Density
ratio of the mass of a material to the volume that material occupies.

- Static pressure drop gauge
- Inlet and outlet temperature gauges

Cyclones collectors are usually not equipped with opacity monitors due to the limited light-scattering characteristics of the moderate-to-large diameter particles collected in these units.

Static Pressure Drop Gauges

The static pressure drop across the unit is dependent mainly on the inlet gas velocity and the physical condition of the cyclonic collector. The inlet gas velocity is dependent directly on the gas flow rate, which in turn is a function of the process operating rate. At a given process operating rate, the pressure drop is dependent almost exclusively on the physical condition of the collector. This fact can be used to evaluate mechanical problems within the collector that could impair performance. An increase in the pressure drop at a given process operating rate could indicate solids plugging at the inlet to the cyclone tubes of multi-cyclone collectors. A decrease in the pressure drop at a given process operating rate could be due to a variety of problems:

- Erosion of the inlet turning vanes in multi-cyclone collectors
- Erosion of the outlet tubes in multi-cyclone collectors
- Failure of one or more of the gaskets on the clean side tube sheet of multi-cyclone collectors

The static pressure gauge provides the only data that can be used to readily identify these problems while the unit is operational. This relatively inexpensive instrument is very useful.

Installing a temperature gauge at the inlets and outlets is an inexpensive way to monitor efficiency.

Inlet and Outlet Gas Temperature Gauges

Air infiltration is a common problem with multi-cyclone collectors serving combustion sources. It is caused by frequent thermal expansion and contraction as the boiler load varies, by erosion of the solid discharge valve, and by aging of the high temperature gaskets. Air leaking into the hopper area of a multi-cyclone collector can significantly reduce the particulate removal efficiency. The inrushing air re-entrains particulate matter from the hopper and disrupts the vortices in the cyclone tubes as it moves upward toward the outlet tubes.

The onset of air infiltration problems can be readily identified by the gas temperature drop across the unit. The relatively cold ambient air dilutes the flue gas stream and increases the temperature drop across the unit. A multi-cyclone collector with a gas temperature drop of more than about 25°F probably has significant air infiltration, assuming that the temperature data are correct and representative. Increases in the gas temperature drop of 5 to 10°F from the baseline range (at a given boiler load) are also indicative of significant air infiltration. The cost of the temperature gauges at the inlet and outlet is relatively small compared to the benefits provided with respect to the early identification of air infiltration problems. The temperature gauges are usually mounted in the inlet and outlet ductwork.

Review Questions

1. What is the normal range of inlet gas stream velocity for large diameter cyclones? (page 3)
    a. 5 to 10 feet per second
    b. 20 to 50 feet per second
    c. 5 to 10 feet per minute
    d. 20 to 50 feet per minute

2. What is the purpose of using a solids discharge valve on the hoppers of cyclone collectors? Select all that apply. (page 6)
    a. Minimize air infiltration into the cyclone
    b. Minimize the risk of fires
    c. Maintain solids flow out of the hopper

3. What design feature initiates the spinning gas flow in a large diameter cyclone? (page 4)
    a. Turning vanes
    b. Gravity
    c. Tangential gas inlet
    d. None of the above

4. Which type of cyclone collector has higher radial velocities? (page 2)
    a. Large diameter cyclones
    b. Multi-cyclones

5. What is the purpose of the clean side tube sheet in a multi-cyclone collector? (page 6)
    a. Support the cyclone tubes
    b. Separate the inlet gas stream from the outlet gas stream
    c. Separate the outlet gas stream from the hopper
    d. None of the above

6. What is the typical number of complete turns (360 degrees) achieved in a large diameter cyclone operating with a normal inlet gas velocity? (page 3)
    a. One-half to three
    b. Two to five
    c. Five to ten
    d. Greater than ten

7. What is the typical range in the diameters of multi-cyclone tubes? (page 6)
    a. 1 to 6 inches
    b. 6 to 12 inches
    c. 12 to 18 inches

d. 18 to 24 inches

8. Must multi-cyclone tubes be oriented vertically (inlet at top, cyclone discharge at bottom) in order to operate properly? (page 6)
   a. Yes
   b. No

9. Why is it important to fabricate the outlet extension tubes of multi-cyclone collectors from abrasion resistant material? (page 3)
   a. Minimize abrasion caused by the inlet gas stream
   b. Minimize abrasion caused by the outlet gas stream
   c. Minimize fracturing the inlet particulate matter
   d. All of the above

10. The performance of a cyclone collector is related to the ___ of the particle diameter.
   a. First power
   b. Second power
   c. Third power
   d. Performance is independent of particle size

11. The performance of a cyclone collector is related to the __ of the gas velocity.
   a. First power
   b. Second power
   c. Third power
   d. Performance is independent of radial gas velocity

12. Static pressure drop across a cyclone collector is related to the __ of the gas flow rate.
   a. First power
   b. Second power
   c. Third power
   d. Static pressure drop is independent of gas flow rate

13. Typical static pressure drops in a multi-cyclone collector are:
   a. 1 to 3 in WC
   b. 4 to 6 in WC
   c. 1 to 3 psig
   d. 2 to 6 psig

14. Multi-cyclone collectors are capable of effectively removing particles down to approximately _______ micrometers.
   a. 0.5 micrometers
   b. 3 micrometers

c. 10 micrometers
d. 20 micrometers
e. 50 micrometers

Review Question Answers

1. What is the normal range of inlet gas stream velocity for large diameter cyclones? (page 3)
b. 20 to 50 feet per second

2. What is the purpose of using a solids discharge valve on the hoppers of cyclone collectors? Select all that apply. (page 6)
a. Minimize air infiltration into the cyclone
b. Minimize the risk of fires
c. Maintain solids flow out of the hopper

3. What design feature initiates the spinning gas flow in a large diameter cyclone? (page 4)
c. Tangential gas inlet

4. Which type of cyclone collector has higher radial velocities? (page 2)
b. Multi-cyclones

5. What is the purpose of the clean side tube sheet in a multi-cyclone collector? (page 6)
b. Separate the inlet gas stream from the outlet gas stream

6. What is the typical number of complete turns (360 degrees) achieved in a large diameter cyclone operating with a normal inlet gas velocity? (page 3)
a. One-half to three

7. What is the typical range in the diameters of multi-cyclone tubes? (page 6)
b. 6 to 12 inches

8. Must multi-cyclone tubes be oriented vertically (inlet at top, cyclone discharge at bottom) in order to operate properly? (page 6)
b. No

9. Why is it important to fabricate the outlet extension tubes of multi-cyclone collectors from abrasion resistant material? (page 3)
a. Minimize abrasion caused by the inlet gas stream

10. The performance of a cyclone collector is related to the ___ of the particle diameter.
b. Second power

11. The performance of a cyclone collector is related to the __ of the gas velocity.

b. Second power

12. Static pressure drop across a cyclone collector is related to the __ of the gas flow rate.
b. Second power

13. Typical static pressure drops in a multi-cyclone collector are:
b. 4 to 6 in WC

14. Multi-cyclone collectors are capable of effectively removing particles down to approximately _______ micrometers.
b. 3 micrometers

Review Problems

1. What is the overall collection efficiency for a single cyclone collecting dust with the distribution given below? The collector has a diameter of 1 ft, an inlet gas velocity of 50 ft/sec, and an operating temperature of 200°F? The particle density is 70 lb_m/ft^3. Assume the gas stream spins two complete rotations within the cyclone.

Size (μm)	**% of Mass**
10	1
20	3
30	9
40	13
50	24
60	29
70	15
80	4
100	2
	100%

2. A single cyclone collector has the following fractional efficiency curve. Estimate the overall collection efficiency of a dust with a d_{50} of 50 μm and a σ_g of 1.67.

Review Problem Solutions

1. What is the overall collection efficiency for a single cyclone collecting dust with the distribution given below? The collector has a diameter of 1 ft, an inlet gas velocity of 50 ft/sec, and an operating temperature of 200°F? The particle density is 70 lb_m/ft^3. Assume the gas stream spins two complete rotations within the cyclone. (page 10)

Size (μm)	**% of Mass**
10	1
20	3
30	9
40	13
50	24
60	29
70	15
80	4
100	2
	100%

2. A single cyclone collector has the following fractional efficiency curve. Estimate the overall collection efficiency of a dust with a d_{50} of 50 μm and a σ_g of 1.67. (page 10)

Solution to #1

Estimate the gas viscosity at 200°F:

$$\mu = \mu_{ref}\left(\frac{T}{T_{ref}}\right)^{0.768} = 1.21x10^{-5}\frac{lb_m}{ft\cdot\sec}\left(\frac{660°R}{528°R}\right)^{0.768} = 1.44x10^{-5}\frac{lb_m}{ft\cdot\sec}$$

Calculate the cut diameter:

$$\left[d_p\right]_{cut} = \sqrt{\frac{9\mu_g B}{2\pi n_t v_i \rho_p}} = \sqrt{\frac{9\left(1.44x10^{-5}\frac{lb_m}{ft\cdot\sec}\right)1\,ft}{2\pi(2)\left(50\frac{ft}{\sec}\right)\left(70\frac{lb_m}{ft^3}\right)}} = 5.43x10^{-5}\,ft = 16.5\mu m$$

Calculate the fractional efficiencies:

Problem 6-1 Efficiency Estimates		
$[d_p]_i$ (μm)	$[d_p]_i/[d_p]_{cut}$	η_i (%)
10	0.6	28
20	1.2	55

30	1.8	74
40	2.4	83
50	3.0	90
60	3.6	94
70	4.2	97
80	4.8	98
100	6.1	100

Calculate the overall efficiency:

Size (μm)	% of Mass	η_i (%)	Mass collected (%)
10	1	28	0.28
20	3	55	1.65
30	9	74	6.66
40	13	83	10.79
50	24	90	21.60
60	29	94	27.26
70	15	97	14.55
80	4	98	3.92
100	2	100	2.00
	100%		88.71%

Solution to #2

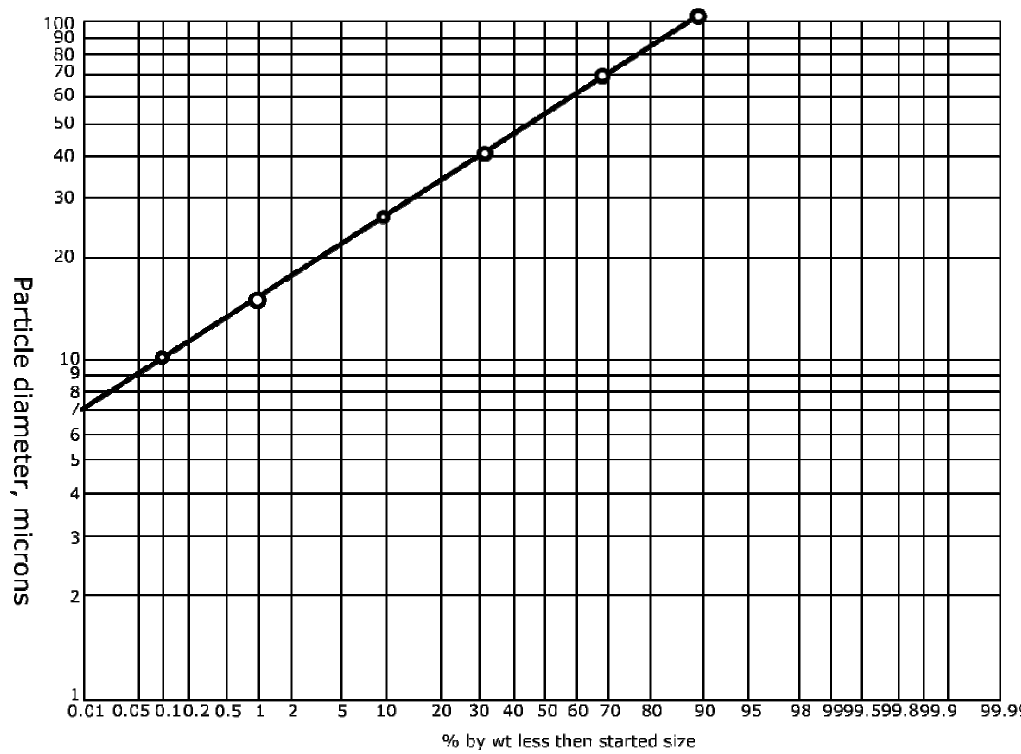
Plot cumulative distribution plot, divide into particle size ranges and determine the percent mass in each size range:

Size (gm)	% of Mass Less Than Size	Size Range (μm)	% of Mass
10	0.1	0 to 10	0.1
15	1.0	10 to 15	0.9
26	10.0	15 to 26	9.0
40	32.0	26 to 40	22.0
67	70.0	40 to 67	38.0
100	90.0	67 to 100	20.0
		>100	10.0

Calculate the overall efficiency:

Size Range (gm)	Avg Size (gm)	% of Mass	η_i (%)	Mass Collected (%)
0 to 10	5.0	0.1	28	0.03
10 to 15	12.5	0.9	52	0.47
15 to 26	20.5	9.0	68	6.12
26 to 40	33.0	22.0	82	18.04

40 to 67	53.5	38.0	93	35.34
67 to 100	83.5	20.0	99	19.80
>100	100.0	10.0	99	9.90
		100%		89.70%



References

Lapple, C.E., "Processes use many collection types", *Chemical Engineering,* **58,** 145 (1951).

Leith, D., and W. Licht, "The collection efficiency of cyclone type particle collectors—a new theoretical approach", *AIChE Symposium Series,* Vol. 68, No. 126 (1973).

Shepard, C.B., and C.E. Lapple, "Flow pattern and pressure drop in cyclone dust collectors", *Industrial and Engineering Chemistry,* **31,** 972 (1939).